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Gas recirculation impact on the nitrogen oxides formation in the boiler furnace

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Abstract

The structural features of the fire-tube boilers furnaces are considered. The numerical calculations data of the turbulent combustion in reversing and flow furnaces for gas fuel are presented in the paper. Gas mixture temperature minimum values in volume and nitrogen oxides concentration correspond to the reversing furnace.

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Keywords: fire-tube boiler; reversing furnace; combustion; temperature; nitrogen oxides

1. Introduction

Originally, the steam and hot-water boilers constructions development was carried out in the following two areas: the fire-tube and watertube methods of heat-carrier heating. In the first case combustion products were moving inside the separating surface while water washed the heating surface outside, in the second case the heat carrier moved inside, while exhaust gases did outside.

Combined fire-tube boilers, where the fire tube performed as a furnace while smoke tubes performed as the convection surface, had the greatest heating surface (up to 300 m^2). On exhaust gases circulation there are units having an exhaust gases reverse in the fire tube or double reverse and triple one of the exhaust gases [1,2].

The main toxic component formed at the natural gas and fuel oil combustion in the fire-tube boilers furnaces is nitrogen oxides NO_x. Nitrogen oxides have a negative impact on human health, on the respiratory system in

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particular. Although naturally formed nitrogen oxides quantity exceeds the emissions from human activity results, it is necessary to take into consideration that anthropogenic emissions of nitrogen oxides are localized in the human economic activity places. Therefore NO_x concentration in urban areas is higher than the natural background concentration.

The objective of the study is the gaseous fuel combustion calculation research in the fire-tube boilers furnaces with simultaneous nitrogen oxides emissions limitation. The given processes are still insufficiently studied with regard to the low-powered boilers and attract the particular interest when modern autonomous heat supply sources developing.

2. The nitrogen oxides formation processes modelling

The main toxic component formed at the natural gas and fuel oil combustion in the fire-tube boilers furnaces is nitrogen oxides NO_x. Nitrogen oxides have a negative impact on human health, on the respiratory system in particular [3].

At the fossil fuels combustion in the boilers furnaces, the nitrogen contained in the fuel and air while interacting with the oxygen forms the following oxides: NOx = NO + NO2+ N2O.

The nitrogen oxides NOx main share (95...99 %) formed in steam and hot-water boilers combustion products accounts for nitrogen monoxide (oxide) NO. Dioxide NO_2 and nitrous oxide N_2O are formed in significantly less amounts.

Nitrogen monoxide (oxide) is formed at the fossil fuel combustion both by means of nitrogen oxidation N2 of the air and nitrogen oxidation contained in the fuel. Nowadays three mechanisms, whereby nitrogen oxides are formed: thermal, prompt, fuel ones, are known. At the thermal and prompt NO formation, the source of nitrogen is the air and in case of the fuel NO formation it is nitrogen-containing fuel components [3,4].

3. Methods

To characterize the reacting gases turbulent flows, the turbulence model with two equations is used. In the model the velocity and characteristic length values are defined using various transport equations (hence the term "two equations"). The given turbulence model was named k-ε (k is the turbulent kinetic energy, ε is the kinetic energy dissipation value) [4, 5, 6].

Let's consider the main equations describing reacting gas mixture under the following principal assumptions: gas mixture filling the furnace volume is the grey body; the heat from the torch to the wall is mainly transferred by radiation and convection; inside the boundary layer the pressure does not change along the normal to the body circuit and is equal to the corresponding pressure on the boundary layer external edge; inside the temperature boundary layer, the terms characterizing the energy change in consequence of convection and time variation are of the same order of magnitude with the terms characterizing the energy change as a result of molecular thermal conductivity; the total heat transfer on the gas mixture - wall boundary line is performed by means of the convective heat transfer and radiation; the reacting gas CH_4 – 100 %, oxidizer is air.

- The continuities for the whole mixture:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \boldsymbol{U} \right) = 0 \tag{1}$$

where ρ is the gas mixture density; U is the velocity vector; t is the time.

- The continuities for every component:

$$\frac{\partial(\rho Y_I)}{\partial t} + \frac{\partial(\rho u_j Y_I)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_{Ieff} \frac{\partial Y_I}{\partial x_j} \right) + S_I \tag{2}$$

S_I is the velocity of I-component forming (it is defined taking into account the kinetic scheme of methane oxidation)

$$Y_I = \frac{\rho_I}{\rho}$$

is the I-component substance concentration; ρ_I is the I-component density;

$$\Gamma_{Ieff} = \Gamma_I + \frac{\mu_t}{Sc_t}$$

is the diffusion coefficient; Γ_I is the diffusion coefficient for $_I$-component; μ_t is the dynamic viscosity turbulent component;

$$Sc_t = \frac{\nu}{\Gamma_I}$$

is the Schmidt number; ν is the kinematic viscosity.

- The moments:

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \bullet (\rho \boldsymbol{U} \otimes \boldsymbol{U}) - \nabla \bullet (\mu_{eff} \nabla \boldsymbol{U}) = -\nabla P' + \nabla \bullet (\mu_{eff} \nabla \boldsymbol{U})^T + \boldsymbol{B} \tag{3}$$

where B is the sum of all the forces acting upon the gas volume, μ_{eff} is the efficient turbulent viscosity, P is the pressure.

- The energies and dissipations:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon \tag{4}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \bullet (\rho \boldsymbol{U} \varepsilon) = \nabla \bullet \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon) \tag{5}$$

where $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, σ_ε are the informative constants [5]; Pk is the turbulence parameter characterizing the viscosity forces and buoyancy ones P_{kb} ratio [5]:

$$P_k = \mu_t \nabla \boldsymbol{U} \bullet (\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^T) - \frac{2}{3} \nabla \bullet \boldsymbol{U} (3\mu_t \nabla \bullet \boldsymbol{U} + \rho k) + P_{kb} \tag{6}$$

- The viscosity evaluation:
  k- ε model is based on the turbulent viscosity conception, therefore

$$\mu_{eff} = \mu + \mu_t \tag{7}$$

where μ is the dynamic viscosity. In this model the turbulent viscosity μ_t is supposed to be connected with the turbulent kinetic energy and dissipation by means of the following equation:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{8}$$

where C_μ is the informative constant[5].

The variables k and ε are the result of the differential transport equations solving for the turbulent kinetic energy and dissipation:

- the equation of state:

The equation of state offered by Redlich-Kwong is as follows [4]:

$$P = \frac{RT}{\upsilon - b + c} - \frac{a(T)}{\upsilon(\upsilon + b)} \tag{9}$$

where υ is the specific volume. The values a, b, c are the constants depending on the substance.

The initial conditions. The variables values included in the system of equations at the time of t = 0 and the initial temperature of T = 300 K are accepted.

The boundary conditions. The variables values included in the system of equations on the basis of recommendations are accepted [5].

The calculations of nitrogen oxides concentrations in the furnace volume under the turbulent combustion is conducted by the probabilistic method.

4. Results and discussion

The calculations results on the turbulent combustion k-ε model taking into consideration the reacting gases radiation (the radiation model P1) by the ANSYS-CFX applying, carried out for the fire-tube boiler furnace having the capacity of 200 kW are presented below. The furnace length is 1 meter. Fuel is natural gas, oxidizer is air. Methane supply velocity is constant (40 m/s), oxidizer supply velocity is variable.

Gas mixture temperature in the furnace volume is the key parameter for the boiler operational efficiency determination. Furthermore, at the given unit computation it is necessary to define the nitrogen oxides concentrations forming under the combustion process.

The gas mixture recycling phenomenon is common for the fire-tube boilers furnaces.

Gas mixture flow is performed in the open-cycle system and characterized by the recirculation ratio r. The value of r varies from 0 to 1. Moreover, 0 is the flow furnace characteristic, 1 is the reversing furnace one. The intermediate values r describe gas flow processes for the flow furnace with different inlet and outlet diameters ratio.

Figure 1 presents the maximum temperature T variation on the recirculation ratio r. As the graph shows the increase of gas mixture reversion rate results in the decrease both of the flame heart temperature and maximum furnace volume one.

The NO concentration dependence on the recirculation ratio r is shown in Fig. 2. NO values changing is defined by the temperature variation law in volume characterized by the recirculation ratio in all the studied range for the given values. NO maximum values correspond to the flow furnace at $r \rightarrow 0$. NO minimum values correspond to the reversing furnace at $r \rightarrow 1$.

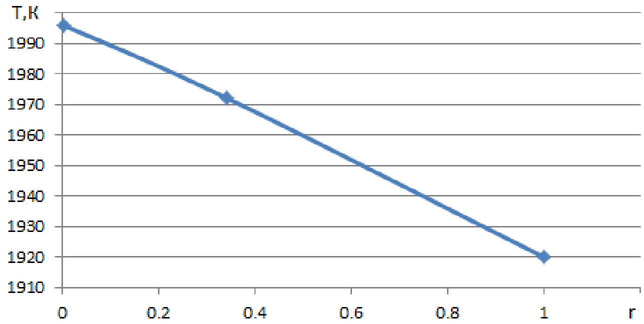

Fig. 1. The maximum temperature T dependence on the recirculation ratio r.

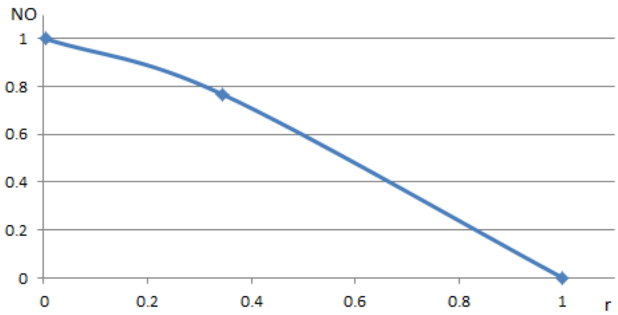

Fig. 2. The NO concentration dependence on the recirculation ratio r.

5. Conclusion

The fire-tube boilers furnaces combustion processes were shown to be always followed by the gas flow (air, gaseous fuel, combustion products) and represent the complex of aerodynamic, heat and chemical processes. Under the fossil fuel combustion the nitrogen monoxide (oxide) is formed by means of the air nitrogen oxidation.

Recirculation inside the furnace results in the furnace outlet nitrogen oxides concentrations decreasing in consequence of the convection phenomena intensification and gas temperature reduction.

Recirculation maximum value corresponds to the reversing furnace in low and medium power boilers.

References

[1] D. Annaratone, Steam generators, Springer-Varlag, Berlin, Heidelberg, 2008, 434 p.
[2] A.G. Mihajlov, P.A. Batrakov, Jeffektivnye poverhnosti teploobmena v topke gazotrubnogo kotla :monogr, Omsk, OmGTU, 2014, 120 p. (In Russian)
[3] P.V. Rosljakov, I.A. Zakirov, Nestehiometricheskoe szhiganie prirodnogo gaza i mazuta na teplovyh jelektrostancijah, M. : MJeI, 2001, 144 p. (In Russian)
[4] C.P. Fenimore, Formation of nitric oxide in premixed hydrocarbon flame , 13-thSympos. (Interm.) On Combustion, 1971, 373 p.
[5] ANSYS CFX-Solver Theory Guide. ANSYS CFX Release 11.0. ANSYS, Inc.,Southpointe 275 Technology Drive, Canonsburg: PA 15317, 2006, 312 p.
[6] D.B. Spolding, Calculations of Combustion Processes, Rep-t. RF.TN.A. 1–8, 1971, Dept. Of Mechanical Engineering, Imperial College, London, England.
[7] J. Warnatz, U. Mass, R.W. Dibble, Combustion, Springer-Varlag, Berlin, 1996, pp. 219–221.